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Finite element analysis of thermoelectric refrigeration system

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Abstract

The numerical analysis of a thermoelectric refrigeration system was carried out by the finite element method, using ANSYS V13 software. The geometrical model was developed and analysed, with design modular and thermal-electric mechanical multi physic solver interface. Bi-Te and Pb-Te thermoelectric modules were considered for analysing their performance. The current and temperature differences between the hot side and cold sides were varied, to study the characteristics of the thermoelectric module. The COP for the Bi-Te system was 13.4% higher compared to the Pb-Te under the same operating conditions. The optimal current and voltage increased linearly with an increase in the differential temperature. The heat absorbed by the Bi-Te system was 28.42 % higher than that by the Pb-Te. It was concluded that even though the figure of merit is higher for the Pb-Te at a very high temperature range between 400- 600 K, it shows a lower performance compared to the Bi-Te, when it is operated at ambient temperature conditions.

Keywords: Thermoelectric; Finite element analysis; Peltier effect.

Nomenclature

c	heat capacity (J/kg.K)
E	electric field(V/m)
I	current (A)
J	current Density (A/m^2)
k	thermal conductivity(W/Cm. K)
N	element shape function
q	heat flux (W/m^2)
Q	internal heat generation (W)
t	time (S)
T	temperature (K)
Z	figure of merit
Q_C	heat absorbed at cold side (W)
COP	coefficient of Performance

Greek symbols

σ	electrical conductivity (S/m)
α	seebeck Coefficient (V/K)
ε	electric permittivity (F/m)
ρ	density (Kg/Cm^3)
Π	peltier Coefficient (J/V)
ϕ	electrical potential (V)

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1. Introduction

Peltier technology has experienced a major advance in recent years, mainly due to the development of semiconductor materials. Thermoelectric coolers are solid-state heat pumps, which remove heat from one side and dissipate that energy to another side. This process is, in general, governed by reversible and irreversible thermal to electrical energy transformations. The main reversible effect is the Peltier effect. The Peltier effect determines the cooling potential of the device, whereas the irreversible Joule heating and Fourier effect degrade the overall cooling performance [1].

The absence of the moving parts makes the thermoelectric system very reliable; it gives approximately 10^5 hrs of operation at 100° C, and longer life at lower temperatures [2]. Some of the advantages of thermoelectric refrigeration systems are precise temperature control, the ability to lower the temperature below the ambient, controlled heat transport by current input, and the ability to be operative in any orientation. Their compact size makes them useful for applications where size or weight is a constraint, the ability to alternate between heating and cooling is important and an excellent cooling alternative to vapor compression coolers is needed for systems that are sensitive to mechanical vibration. The electronic, medical, aerospace and telecommunication industries are other important areas for thermoelectric cooling applications. [3,4]

Thermoelectric coolers are based on the Peltier effect; when a voltage or DC current is applied to two dissimilar conductors, a circuit can be created that allows for continuous heat transport between the conductor's junctions. The Seebeck effect is the reverse of the Peltier Effect [5].

The current is transported through charge carriers (In the direction opposite to the hole flow, or in that of electron flow). Heat transfer occurs in the direction of the charge carrier movement. The efficiency of a thermoelectric material [6] is given by the Figure Of Merit Z, which is defined as

$$Z = \frac{\alpha^2 \sigma}{k} \tag{1}$$

The Seebeck Coefficient (α), is given by eq. (2)

$$\alpha = \frac{E}{dT / dx} \tag{2}$$

Low electrical resistivity and thermal conductivity are required for a high figure of merit. These values are temperature dependent. Therefore, the figure of merit depends on the temperature. P and N type thermoelectric materials have different figures of merit, and are averaged to determine the material's overall quality [6].

In the present work, a one dimensional steady state thermoelectric cooling problem, with a single pair thermoelectric module, was considered for the analysis, as shown in Figure 1. The thermoelectric material properties vary with absolute temperature. Heat is absorbed in the cooling surface maintained at temperature T_C and the heat is rejected by a heated surface, maintained at temperature T_H. Bismuth tellurium (Bi-Te) and lead tellurium (Pb-Te) with a cross sectional area of 0.6 x 0.6 mm^2 and a length of 0.5 mm were considered as solid thermoelectric P and N semiconductor materials. The main objectives of this analysis were to (1) Develop a computational model that simulates the thermoelectric refrigeration system, (2) Analyse the thermoelectric refrigeration system by varying the operating parameters like current and temperature difference and (3) Compare the performance of the Bi-Te and Pb-Te thermoelectric couples.

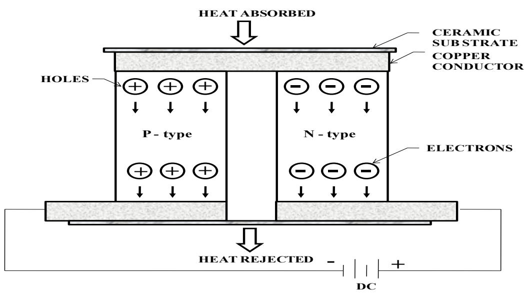

Fig. 1 Single couple thermoelectric module

2. Computational details

The equations [7] to describe the behaviour of a thermoelectric material are governed by the couple equations of heat transfer and the continuity of current density phenomena, which are given by eq.(3) and (4):

$$\rho c \frac{\partial T}{\partial t} + \vec{\nabla}.\vec{q} = Q \tag{3}$$

$$\vec{\nabla}.\left(\varepsilon \frac{\partial \vec{E}}{\partial t} \right) + \vec{\nabla}.\vec{J} = Q \tag{4}$$

The electrical current density is generated by the coupling of the irreversible Joule effect and the reversible Seebeck effect, as shown in eq.(5)

$$\vec{J} = \sigma \vec{E} - \sigma \alpha \vec{\nabla} T \tag{5}$$

The heat flux $\vec{q}$ is generated by the reversible Peltier and irreversible Fourier effect, as shown in eq.(6)

$$\vec{q} = \Pi \vec{J} - k \vec{\nabla} T \tag{6}$$

The electric field $\vec{E}$ is derived from the electric scalar potential φ as shown in eq. (7)

$$\vec{E} = -\vec{\nabla} \phi \tag{7}$$

Finite element equations are transformed from the two coupled governing equations (3) and (4) by approximating the primitive physical unknowns, temperature T and electrical potential ϕ, into interpolation functions, and the value of the nodal known on an element as shown in eq. (8,9)

$$T = [N]\{T_e\} \tag{8}$$

$$\phi = [N]\{\phi_e\} \tag{9}$$

where ϕ_e is the vector of nodal electrical potential, T_e is vector of nodal temperature, and N is the element shape function. After the manipulations based on the Galerkin weighting scheme [5], the differential equations (From eq.7 to 9) become algebraic finite element equations, as shown in eq. (10).

$$\begin{bmatrix} C_T & 0 \\ 0 & C_E \end{bmatrix} \begin{Bmatrix} \dfrac{\partial T^2}{\partial t} \\ \dfrac{\partial \phi^2}{\partial t} \end{Bmatrix} + \begin{bmatrix} K_T & 0 \\ K_{ET} & K_E \end{bmatrix} \begin{Bmatrix} T_e \\ \phi_e \end{Bmatrix} = \begin{Bmatrix} Q \\ I \end{Bmatrix} \tag{10}$$

The above global matrix equation is ordered from the individual finite element equations. The solution yields temperatures, T_e, and electric potentials, ϕ_e, at unconstrained nodes, or reactions in the form of the electric current and, at nodes with the imposed electric potential and temperature respectively.

A numerical simulation was done with ANSYS software, which uses the finite element approach to simulate the physical model. The following procedure is carried out for static thermoelectric analysis:- Creating a physical model, building and meshing the model, assigning physical attributes to each region within the model, applying boundary condition and load, obtaining a solution and reviewing the results. The thermoelectric system considered for the study consists of one pair of P and N semiconductor materials of Bismuth tellurium (Bi-Te) and lead tellurium (Pb-Te), with a cross sectional area of 0.6 x 0.6 mm^2 and a length 0.5 mm. The thermoelectric elements are sandwiched between two copper electrodes, 0.1 mm thick. The material properties of Bi-Te and Pb-Te, [6] for the calculations with temperature independent values are shown in Table 1.

Table 1. Material properties

Materials	Seebeck coefficient(α) [V/K]	Electric Resistivity (ρ) [Ω Cm]	Thermal Conductivity(k) [W/Cm. K]	Density (δ) [kg/Cm^3]	Heat capacity [J/(kg. K)]
Bismuth Tellurium (Bi-Te)	P:200e-6 N:-200e-6	0.9e-5	1.6	77.40e-4	154.4
Lead Tellurium (Pb-Te)	P:175e-6 N:-175e-6	0.8e-5	1.548	81.60e-4	156
copper	6.5e-6	0.169e-8	3.50	89.20e-4	385

3. Results and Discussion

To create the physical environment for an analysis, ANSYS pre-processor is used to establish a mathematical simulation model of the physical problem. The following steps are used to carry out the thermoelectric system analysis: Set the GUI Preferences, define the analysis title, define the element types and options, define the element coordinate systems, Set the real constants and define a system of units and define the material properties. The ANSYS software includes three elements which are used in modelling the thermoelectricity phenomenon. The element types establish the physics of the problem domain.

The different physics regions in the model are meshed, using the finite element method. The number of grid elements was varied from 1900 to 3000, and it is observed that only negligible changes of 1% in temperature and voltage distribution take place. Hence, the default number of elements was chosen for the analysis. 10739 nodes and 1944 elements are generated and meshed for this model analysis.

After generating the mesh, the electrical load and boundary conditions are specified for the model. The temperature was varied from 293K to 363 K, between the cold and hot side of the model. The electrical load of 0.5A to 3.6 A was applied on the vertical face of the copper base across the thermoelectric system. A very low convection loss of 1e^{-6} W/(m K) was applied on all other surfaces, which ensured the adiabatic heat transfer from the cold end to the hot end for the thermoelectric model. The simulation outputs from the model are temperature, heat flow and voltage distribution.

For The Bi-Te and Pb-Te thermoelectric couples, the computationally generated mesh, temperature and voltage distribution are shown in Figure 2 and Figure 3 respectively.

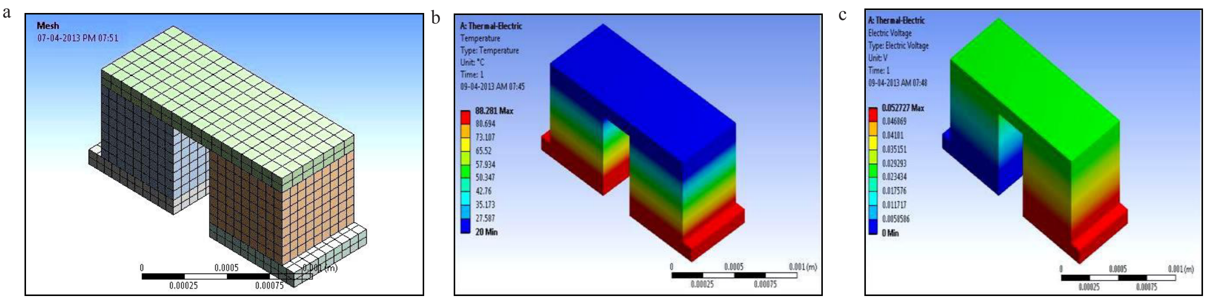

Fig. 2. (a) Computational mesh for Bi-Te module (b) Temperature distribution of Bi-Te module (c) Voltage distribution Bi-Te module

a b c

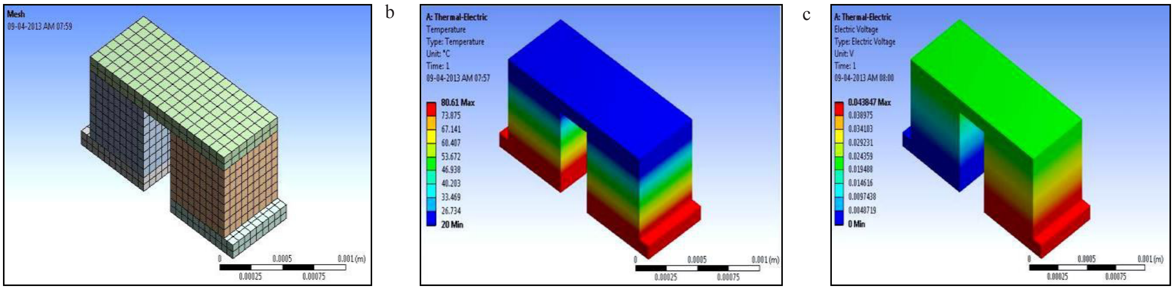

Fig. 3. (a) Computational mesh for Pb-Te module (b) Temperature distribution Pb-Te module (c) Voltage distribution Pb-Te module

The variation of the COP for the thermoelectric element with current is shown in Figures 4 and 5 respectively. It is found that the COP increases till an optimum current is reached, and then decreases with further increase in the current. A maximum COP of 1.1 and 0.92 were obtained for the Bi-Te and Pb-Te systems at 30 K differential temperature.

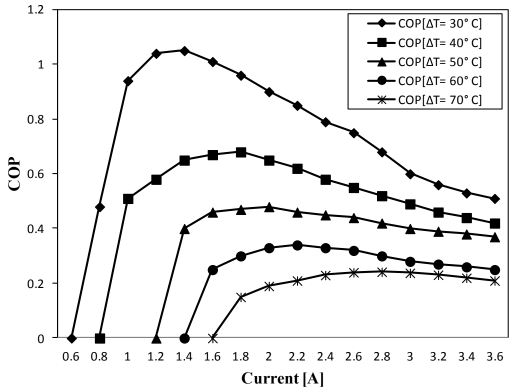

Fig. 4. Variation of COP for Bi-Te system with current

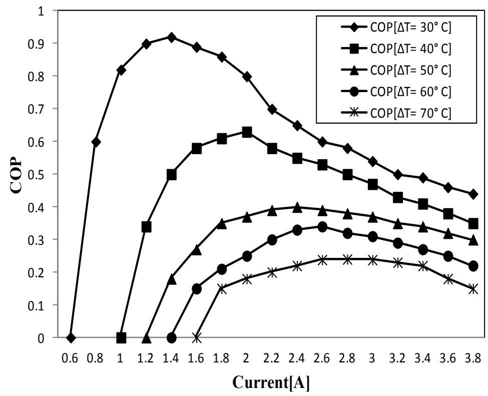

Fig. 5. Variation of COP for Pb-Te system with current

The Bi-Te couple has 13.46% higher COP when compared to the Pb-Te couple under the same operating conditions. The optimal COP decreases with an increase in the differential temperature, as shown in figure 6. The variation of the optimal current with differential temperature is shown in Figure 7. The optimal current for the maximum COP increases with an increase in the differential temperature.

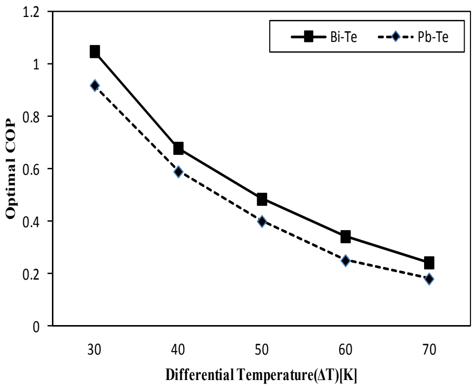

Fig. 6. Variation of optimal COP with differential temperature

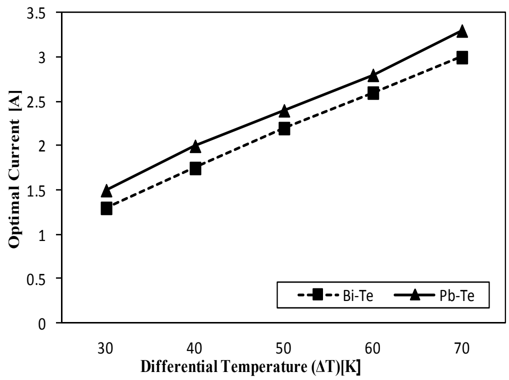

Fig. 7. Variation of optimal current with differential temperature

The variation of the optimal heat absorbed with differential temperature is shown in Figure 8. The amount of heat absorbed (Q_C) on the cold side increases up to the optimal temperature difference, and then decreases with an increase in the differential temperature. A maximum of 0.095 W heat is absorbed at the temperature difference of 40 K in the Bi-Te system, which is 28.42 % higher compared to that of the Pb-Te system. The variation of the optimal voltage with differential temperature is shown in Figure 9. The voltage drop for the Bi-Te and Pb-Te modules is 52 mV and 43 mV respectively when operating at 40 K temperature difference and it increases with an increase in the differential temperature.

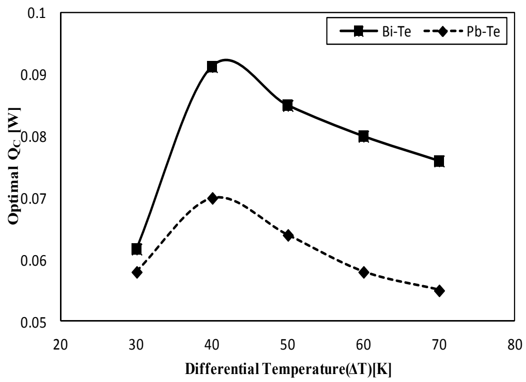

Fig. 8. Variation of optimal Q_C with differential temperature

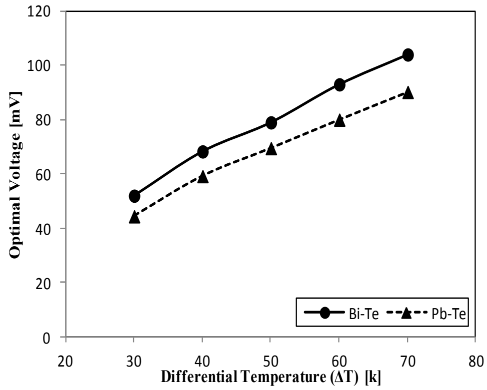

Fig. 9. Variation of optimal Voltage with differential temperature

4. Conclusion

A study on the behaviour of the thermoelectric refrigeration system was carried out using ANSYS software. The governing equations were transformed into algebraic equations via FEM discretization technique. Bi-Te and Pb-Te semiconductor materials were considered for the analysis. The result shows that the COP of the thermoelectric refrigeration system decreases with an increase in the temperature difference. The COP of the Bi-Te system is 13.46% higher than that of the Pb-Te system, under the same operating conditions. The optimal current and voltage increase linearly with an increase in the differential temperature. The heat absorbed on the cold side reaches the maximum at an optimal temperature difference; a maximum of 0.095 W heat was absorbed at the temperature difference of 40 K in the Bi-Te system, which is 28.42 % higher compared to that of the Pb-Te system. It was concluded that even though the Figure Of Merit is higher for Pb-Te in the temperature range of 400-600K, it shows a lower performance compared to Bi-Te, when it is operated at ambient temperature conditions. Hence, Bi-Te is considered as the better choice for ambient applications, while Pb-Te better for high temperature applications.

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